ARMY RESEARCH LABORATORY

Joint Technical Coordinating Group on Aircraft Survivability Interlaboratory Ballistic Test Program

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ARL-TR-755
JTCG/AS-95-V-007

June 1995

JTCG/AS

DEPARTMENT OF MATHEMATICAL SCIENCES
USMA

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1995	Interim FY93-FY94

4. TITLE AND SUBTITLE
Joint Technical Coordinating Group on Aircraft Survivability Interlaboratory Ballistic Test Program

5. FUNDING NUMBERS

6. AUTHOR(S)
John H. Graves and *Captain Hermann Kolev

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-755

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Joint Technical Coordinating Group on Aircraft Survivability

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
JTCG/AS-95-V-007

11. SUPPLEMENTARY NOTES
* Captain Hermann Kolev, Department of Mathematical Sciences, United States Military Academy

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Analysis of experimental data from interlaboratory ballistic tests indicate that results from different facilities are not fully comparable for each of the two armor materials tested. The Materials Directorate of the Army Research Laboratory (ARL•MD) provided each of the nine laboratories participating in this program with a set of metallic armor panels and a set of macrocomposite armor panels consisting of a ceramic adhesively bonded to Kevlar® reinforced plastic. ARL•MD stipulated the velocity for the first projectile fired at each set of armor panels and an obliquity of 0°. The lead test engineer at each laboratory selected all subsequent velocities. Each laboratory shot a series of ARL•MD provided U.S. 0.50 caliber armor piercing (AP) M2 projectiles at the panels and calculated a V_{50} protection ballistic limit (PBL) in accordance with MIL-STD-662E. In this report, we present the results from each laboratory for both armor panel types on which we performed two different statistical analyses. We also include a series of recommendations for improving the reproducibility of interlaboratory ballistic test data.

14. SUBJECT TERMS
Ballistic Tests, Armor, Statistical Analysis

15. NUMBER OF PAGES 49

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

Authors' Forward

Throughout the course of this program, our efforts to gather, analyze, and compare interlaboratory test data met with varying degrees of skepticism by experts in the fields of penetration mechanics and ballistic testing. The combined knowledge and experience of these scientists and engineers is impressive indeed. Many of the participating facilities have performed ballistic tests since the Second World War and have developed excellent reputations. Although the interlaboratory ballistic test series and resultant data have generated a great deal of interest, several distinguished members of the community have made the following observations:

> "If the laboratories don't get the same result, then someone is doing the test wrong;" (The Other Guy is Wrong Syndrome)
>
> "There is no need for this, our results compare very well with another [single] laboratory;" (Selective Validation Syndrome)
>
> "If the data are not comparable, then something must be wrong with the test materials or the projectiles." (Irreproducible Materials Syndrome)

We tried to address these and other concerns insofar as our resources and schedule permitted. The number of test sites needed to be large to satisfy standardized requirements for conducting an interlaboratory test and to justify the use of analytical techniques.[1] The intent of this study was not to pass judgment on any specific or "correct" way to do a ballistic test, but rather to *quantify* any existing variability between laboratories. For this reason, each laboratory was assigned a random number from 1 to 9 so the results could be presented anonymously, without a particular set of results being linked to a particular laboratory. In this way, we hoped to preclude subjective or prejudicial ranking of the laboratories based on reputation or capabilities rather than results. We also went to great lengths to ensure the uniformity of both the armor materials and projectiles. It is our sincere hope that this work will serve as a catalyst for refining and standardizing ballistic test methodology, analysis, and data reporting requirements.

Background and Definitions

For over 40 years, scientists and engineers have grappled with the problem of how to evaluate and analyze the ballistic performance of armor materials. Their efforts have been complicated by the large number of independent variables associated with a ballistic test and thus the high costs associated with ballistic testing. Numerous published papers address techniques for reducing and analyzing data.[2, 3, 4, 5] Although significant efforts have been directed at testing and analyzing ballistic performance, concerns regarding the reliability and comparability of ballistic test data still persist.[6]

The statistical value most closely associated with ballistic performance is the V_{50} value, defined as the velocity at which complete penetration or partial penetration of an armor material are equally likely events. There are several types of V_{50} ballistic limits—the Army Criterion, the Navy Criterion, and the Protection Criterion—which are described in the literature.[7] The Protection Ballistic Limit (PBL) V_{50} is the most widely accepted criterion

for assessing the performance of lightweight armor materials and served as the focus for this study. The experimental outcome of the PBL V_{50} ballistic test is determined by the final condition of a witness plate placed behind the armor panel. After the test, the witness plate is placed in front of a light source. If the witness plate is perforated by the projectile or spall from the test panel (evidenced by light visible through the witness plate), that result is termed a *complete penetration*. If no perforation is observed through the witness plate, the result is termed a *partial penetration*. Even if the test panel is perforated but the witness plate remains intact, the result is still defined as a partial penetration. A schematic definition of the partial and complete penetrations is shown in Figure 1. The *zone of mixed results* (ZMR) is the velocity range over which both partial and complete penetrations are observed. MIL-STD-662E, *V_{50} Ballistic Test for Armor*, defines the Protection Ballistic Limit (PBL) V_{50} as follows:

> The V_{50} PBL may be defined as the average of an equal number of highest partial penetration velocities and the lowest complete penetration velocities which occur within a specified velocity spread. The normal up-and-down firing procedure is used. A 0.020 inch (0.51 mm) thick 2024 T3 sheet of aluminum is placed 6 ± 1/2 inch (152 ± 12.7 mm) behind and parallel to the target to witness complete penetrations. Normally at least two partial and two complete penetration velocities are used to complete the BL(P). Four, six, and ten-round ballistic limits are frequently used. The maximum allowable velocity span is dependent on the armor material and test conditions. Maximum velocity spans of 60, 90, 100, and 125 feet per second (ft/s) (18, 27, 30, and 38 m/s) are frequently used.[8]

The main problem with this definition is the extreme latitude it provides in determining V_{50} value. The least stringent requirement is for two partial and two complete penetrations occurring within a velocity range of 125 ft/s. Another variability with this standard is the absence of standard specimen sizes and fixturing methodology. For example, tests on boron carbide and silicon carbide backed by Kevlar and Spectra indicated that fixturing (boundary) conditions have an important effect on ballistic performance in a V_{50} PBL test.[6]

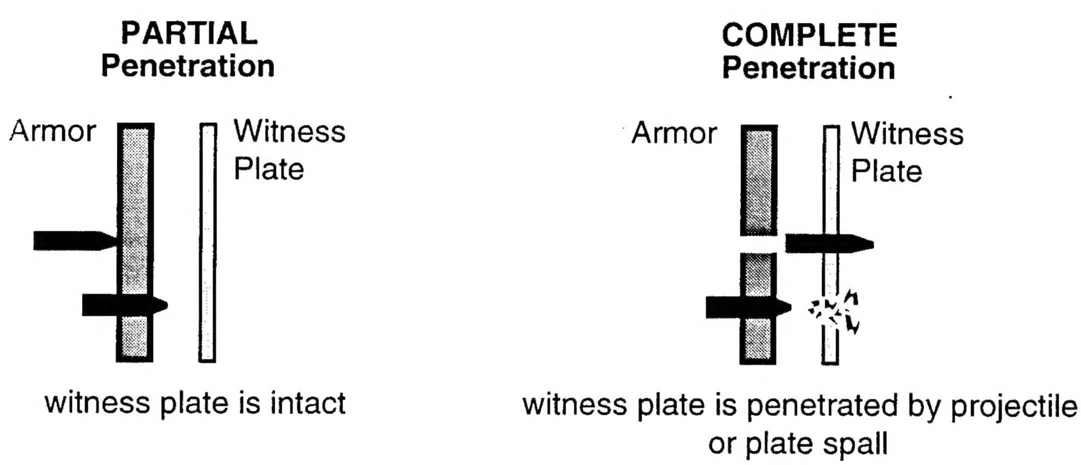


Figure 1: Schematic presentation of partial and complete penetrations.

Even though statistical bases for evaluating ballistic data are established and documented, the practical aspects of conducting a test do not often conform with the statistical requirements for analyzing the data. For example, rudimentary statistical approaches to data analysis require at least 30 and preferably 45 data points. The costs associated with ballistic testing frequently preclude this large sample size. Another approach which relies on the method of maximum likelihood is seldom used because one possible result may be a requirement to repeat the test.[9] To comply with cost and schedule requirements, existing standards permit the use of lower numbers of data points, typically four or six shots. This approach makes ballistic testing relatively straightforward but the calculated ballistic limits have statistically low confidence levels.

Although work on analytical techniques continues, the number of literature references which address the improvements in experimental techniques used to generate the data for statistical analysis and modeling is rather sparse. Testing methodology is an important factor because the models and analysis can only be as good as the data on which they are based. In this respect, our program is different from its progenitors in terms of its approach. Where previous studies have implicitly assumed the established validity of ballistic test data, we sought to quantify the comparability of such data through ***interlaboratory testing***. Many of our colleagues have participated in programs with two or three facilities testing the same material. However, those experiments were not designed to measure precision or reproducibility between the test facilities. We found no literature reference to specifically designed interlaboratory tests with a large number of participants. Even if two or three laboratories could agree on a V_{50} test value, there is no statistical foundation for comparing their results to other laboratories conducting ballistic tests.

The test phase of our project was complicated by different interpretations of the PBL V_{50} test: is it a systems test or a materials test? The answer to this question hinges on how an armor material is defined and its relation to an armor system. An armor systems test is influenced not only by the armor material used, but also by the supporting structure and fixturing technique. A viable materials property test should be reproducible and invariant within a prescribed level of precision A test for the velocity at which the probability of partial penetration equals the probability of complete penetration for a given armor material should have this quality. In other words, the V_{50} test should be a materials test and is not a systems test. It is important, therefore, to distinguish between ballistic testing of armor materials and those on armor systems.

The grouping of different materials to form laminated armor panels and spaced arrays is a complicating factor in defining whether these are armor materials or armor systems. Although each material is included for a specific purpose, their combination may be considered a single entity that is then incorporated into a system. For our purposes, an armor system includes an armor panel or set of armor panels, comprised of one or more different materials, the mechanism used to fasten those materials into a vehicle's structure, and the structure to which the panel is attached. The fastening mechanism is an important component of the armor system because it imposes boundary conditions on performance of the armor materials. These boundary conditions may have a profound effect on

performance during impact by kinetic energy penetrators. If the fastening mechanism is not designed to carry the impact loads associated with the momentum transfer from the projectile to the armor system, the fasteners may fail before the armor material does. In this case, the system (consisting of the armor panel, fixturing, and support structure) effectively fails even though the armor material is not compromised. We include the support structure in this definition because it can also play a part in the momentum transfer associated with impact by a kinetic energy penetrator. This is an important point, because if the structure deforms (plastically or elastically) during impact then it is contributing to the armor system's defeat of the incident penetrator.

The ballistic performance of a material may be described by a probability density function, (PDF), denoted f(x) and defined by the following equation:[10]

$$\int_{-\infty}^{\infty} f(x)\,dx = 1\ , \text{ where } f(x) \geq 0 \text{ and } -\infty \leq x \leq \infty \tag{1}$$

Most engineers assume that V_{50} tests can be described by a normal (or Gaussian) PDF which is defined by the following function:[11]

$$PDF(V) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-(V - V_{50})^2}{2\sigma^2}\right),\ 0 \leq V \leq \infty \tag{2}$$

Where V is the velocity of the projectile and σ the standard deviation from the V_{50} (median) value. For many materials, this appears to be a reasonable assumption. Ballistic tests at Aberdeen Proving Ground (APG) indicate that the normal cumulative distribution function (CDF) fits a considerable number of test conditions.[12] Although most materials seem to obey a normal CDF, there may be materials for which other distribution functions (Lognormal, Weibull, Bimodal) are more representative. The normal CDF is obtained by integration of the normal PDF and is given by:[13]

$$CDF(V) = \int_{-\infty}^{V} \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-(x - V_{50})^2}{2\sigma^2}\right) dx\ ,\ 0 \leq V \leq \infty \tag{3}$$

Plots of the normal PDF and normal CDF are displayed in Figures 2a and 2b.

Some materials, however, may follow bimodal or other distribution functions. For these materials, the response to projectile impact depends on whether or not the projectile shatters (fractures). For each case (shattered or unshattered projectile), a separate CDF can be used to describe the ballistic behavior of the material. The *shatter gap* for the material may be defined as the velocity difference between the lower V_{50} value for the unshattered core CDF and the higher V_{50} value for the shattered core CDF.

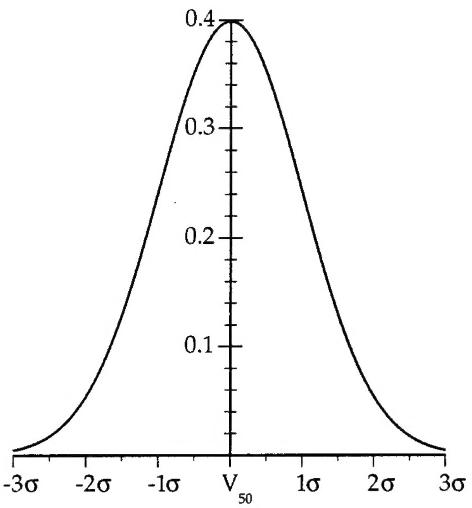


Figure 2a: Normal (Gaussian) Probability Density Function.

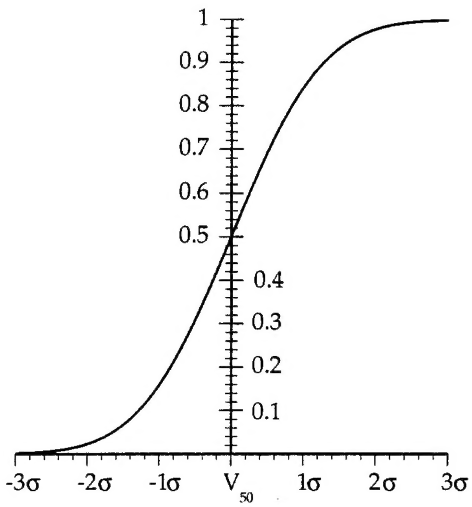


Figure 2b: Normal Cumulative Distribution Function.

Objective

The *Armor Materials Testing and Data Reporting Standards* project was directed towards improving the standards and procedures associated with testing armor materials, not armor systems. A systems test implies a pass-fail criterion while the V_{50} test seeks to determine a more fundamental materials property. The V_{50} test is confined specifically to nonnuclear threats including warhead fragments (non-impulsively loaded), and small arms kinetic energy penetrators. Some of the relevant issues associated with the V_{50} test include establishing the number of shots required to compute a valid V_{50} value, test specimen size, and requirements for test fixturing. Specifically, our objectives were to :

1) determine the precision of ballistic test results between several Government and Industrial laboratories;
2) identify possible sources of bias in ballistic testing;
3) propose methodology improvements to minimize sources of bias;
4) validate the proposed solutions.

Procedure

The interlaboratory testing sequence was designed based on the American Society for Testing and Materials *Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method*, ASTM Standard E691-92. Although the standard may be used when the test result is the average of several two-category (go-no-go) results, additional statistical methods are then required to analyze the data. The standard uses the term *accuracy* to express the closeness of a single test result to the "true" or accepted value. *Precision* is a measure of the degree of agreement among several test results and can be subdivided in terms of *repeatability* and *reproducibility*. Repeatability is a measure of a single laboratory's variability; reproducibility is a measure of variability between laboratories. *Bias* is a measure of the systematic difference between a set of test results and an accepted reference value.[14] In designing an experiment, the standard advises as follows:

> To obtain reasonable estimates of repeatability and reproducibility precision, it is necessary in an interlaboratory study to guard against excessively sanitized data in the sense that only the uniquely best operators are involved or that a laboratory takes unusual steps to get "good" results.

The standard recommends 30 or more laboratories be included in an interlaboratory study (ILS). Under no circumstances may the number of participants be less than 6, with a minimum of 8 required to begin an ILS. In our case, including 30 participants was not practical from a financial standpoint. Our study included 9 participants, thus exceeding the ILS minimum.

We selected participants for the program based on available funding, the number and type of panels selected, and previous experience with research and testing of light weight armor for aircraft applications. Participation of both Government and Industrial laboratories was considered essential. For the Government laboratories, priority was accorded to facilities that have actively participated in activities of the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) Armor & Crew Protection Committee. Participation by Industrial laboratories was solicited through open bidding, which does introduce possible selection bias by choosing those laboratories offering to do the work and submitting acceptable bids. The final list of participants included research organizations with extensive capabilities as well as facilities devoted to product development and quality control. The participants included:

<u>Government Laboratories</u>
Air Force Wright Laboratories
Army Aviation Applied Technology Directorate
Army Research Laboratory, Materials Directorate (Watertown)
Naval Surface Warfare Center

<u>Industrial Laboratories</u>
Ceradyne, Incorporated
H.P. White Laboratories
Simula Government Products
Southwest Research Institute
University of Dayton Research Institute

Materials

The materials selected for use in the ballistic tests needed to be affordable, well characterized, and uniform. To this end, we surveyed published and unpublished data to identify materials for which data already existed. Because the program's sponsor is dedicated to the improvement of aircraft survivability, we concentrated on light weight materials that have been or could be used as aircraft armor. Since our objective was to identify difficulties with the existing military standard for ballistic testing, we made a conscious effort to identify materials that would differentiate variations in the current test methodology. Although testing "well behaved" materials would have produced useful information, it may have also resulted in a false sense of whether the standard's

requirements and procedures effect reproducible and comparable interlaboratory ballistic test data. Our final consideration was a fixed budget which precluded the use of expensive ceramic materials such as boron carbide and silicon carbide. We could have selected these materials, but only by reducing the number of test samples, thus jeopardizing the statistical analysis.

Based on these considerations, we selected two different types of panels for use in this study: one a high strength steel; the other a macrocomposite with a ceramic front face and an aramid reinforced fabric back face.

1) VAR 4340 Steel

Vacuum Arc Remelted (VAR) 4340 steel is widely used in aircraft applications which require high strength and ballistic tolerance. Numerous researchers have characterized the ballistic performance of this alloy as a function of processing and microstructure.[15,16] The vacuum arc remelted (VAR) 4340 steel used to fabricate the steel panels all came from the same heat of material. The panels were rolled to a thickness of 0.375 inch. The panels were commercially heat treated according to the following schedule to obtain a hardness of between 50 and 52 Rockwell C (HRC):

Normalize at 1650°F for two hours and air cool

Austenitize at 1550°F for two hours and oil quench

Temper at 400°F for one hour and air cool

After heat treatment, 0.020 inch was ground from the face of each panel to remove decarburization and scale which might affect the ballistic test results. ARL•MD also took microhardness measurements on the cross section of some panels to determine the extent of decarburization remaining after heat treatment and grinding.

2) Macrocomposite of AD90 Alumina backed by Kevlar Reinforced Plastic

The macrocomposite panels consisted of a single tile of AD90 alumina (Al_2O_3) measuring 5 inches by 5 inches by 0.535 inch adhesively bonded to an eighteen (18) ply Kevlar reinforced plastic (KRP) panel measuring 15 inches square. The panels were all fabricated by a single vendor to a single specification.

Data from previous ARL•MD tests indicated that ceramic/composite armor panels can have markedly different performance, based upon the thickness ratio of front face to back face component.[17] Test data from other research indicated that similar armor panel configurations produced a large zone of mixed results due to unexplainable high velocity partial penetrations.[18] There are other examples of this behavior where the difference between the reported V_{50} value and the highest partial penetration velocity varied by 400 fps in one case and 538 fps in another case.[19,20] Although these studies did not produce enough data to define the cumulative distribution function, they clearly indicate the propensity of ceramic faced, macrocomposite armor panels to exhibit anomalous behavior. In other words, for some configurations it is possible to calculate two different V_{50} values for two different velocity regimes. The participants in the interlaboratory tests were not informed of this behavioral characteristic of the macrocomposite panels in advance of the tests.

Ballistic Testing Methodology

In deciding how many samples each laboratory should test, we desired to have a quantity of panels sufficient to permit valid statistical evaluation, recognizing a requirement for too many panels would render a ballistic test unaffordable for some materials. We decided that three (3) steel panels capable of sustaining eight or nine shots each and sixteen (16) ceramic/Kevlar macrocomposite panels capable of sustaining a single shot represented an effective trade off between available resources and the requirements for statistical analysis.

ARL•MD provided 0.50 caliber AP M2 bullets and primed cases to each participant. We randomly selected the bullets from ARL•MD's bunker; this is also the source of bullets used to produce data contained in *Ballistic Technology of Lightweight Armor* AMMRC TR 81-20—also known as the AMMRC Armor Handbook. Even though the largest single source of small arms ballistic data in the United States was developed with these rounds, we characterized the average hardness for the bullets by randomly selecting and testing ten (10) bullets for Rockwell C Hardness tests. Each laboratory was responsible for providing powder, a target fixture, barrel with firing mechanism, and velocity screens.

We selected a starting velocity of 1600 feet per second (fps) for both the steel panels and the macrocomposite panels. The test director of each laboratory selected all subsequent velocities. The obliquity for all tests was 0°. We did not specify any methodology for the test engineer to use when selecting the next velocity, directing only that each test director use MIL-STD-662E. All of the laboratories used variants of the *up & down* method to select projectile velocities.[9] This technique is based on a bisection algorithm. The advantage of this approach is that relatively few shots are required before a V_{50} value can be calculated. Most of the participants focused their attention in the velocity range from 1400 to 2000 fps for both target types. Only when the test engineer was confident that the V_{50} PBL had been determined did the ARL•MD representative select velocities for the remaining (usually two to four) shots.

There are, however, disadvantages to the up & down approach to velocity selection. The main disadvantage is that it often precludes exploring velocity regimes above and below the apparent V_{50} value. Because the test engineer selects the powder charge (and thereby the projectile velocity), the apparent V_{50} value calculated from the test data is inherently biased. The up & down method assumes a normal distribution with a narrow zone of mixed results (ZMR). If these conditions are not met, then the method will not always produce valid results. The up & down method produces a single V_{50} value and will not help identify the presence of any shatter gap. Finally, the up & down method tends to produce apparent V_{50} values which are either higher or lower than the actual V_{50} value. If the velocity of the first shot is near the actual V_{50} value, MIL-STD-662E requires the second shot be fired at least 100 fps higher or lower than the actual V_{50} value. Whenever the second and third shots result in a low probability result (a complete penetration below the actual V_{50} value or a partial penetration above the actual V_{50} value), the apparent V_{50} value will be driven still further from the actual V_{50} value.

Residual velocities of the bullet, fragments, and spall were not measured. Although residual velocities are important data for vulnerability studies, they add an increment of cost to ballistic testing which was beyond the resources of this program. Moreover, if results from many laboratories do not produce a consensus V_{50} value for a particular type of armor panel, residual velocity measurements cannot possibly agree either. For that reason, we elected to focus this program on characterizing projectile target interactions and defer questions related to residual velocity measurement and behind the armor effects to the future.

Test Results

Each laboratory provided the Project Manager with a report. Although each report had a unique presentation format, they all included a table listing the shot order, target type, impact velocity, and result (partial or complete penetration). We randomly assigned each laboratory a number between 1 and 9, so that the results could be displayed anonymously. We collated the results based on the type of target and the order in which the shots were taken. Table 1 lists the raw velocity data for the steel panels in feet per second (fps); Table 2, for the macrocomposite panels. Since each laboratory received three steel panels, the results are presented for each panel. In addition, Tables 3 and 4 show the velocity increment from one shot to the next for the steel and macrocomposite panels, respectively. MIL-STD-662E typically recommends a velocity increment or decrement of 50 fps or 100 fps.

The data from each laboratory were combined to form a Grand Summary for each type of target panel. This result is displayed graphically in Figure 3. For the steel panels, the difference between the highest partial penetration and the lowest complete penetration is 685 fps; for the macrocomposite panels, 859 fps. Figure 4 is a graphical representation of the penetration data for the steel panels in the velocity range of 1400 to 2000 fps; Figure 5, for the macrocomposite panels in the velocity range of 1500 to 2000 fps. The numbers above and below the graphs indicate the number of partial and complete penetrations above and below the velocity range. The velocity ranges for Figures 4 and 5 encompass approximately 90% of all the data points. The two figures are included to show graphically the comparability of the raw data (partial and complete penetration velocities).

Some of the steel panels were penetrated at velocities below 1500 fps. This runs contrary to published results for this material with a hardness of between 50 and 52 HRC at the areal density used for this series of tests. To determine if decarburization was present, and if so to what depth, ARL•MD sectioned some of the panels and performed microhardness tests. The results of these tests indicate that no more than 0.015 inch of "soft" (less than 48 HRC) material remained on the panel surface.

Table 1. Summary of Steel Velocity (ft/s) Data in Shot Sequence Order.

Shot #	Lab 1	Result	Lab 2	Result	Lab 3	Result	Lab 4	Result	Lab 5	Result	Lab 6	Result	Lab 7	Result	Lab 8	Result	Lab 9	Result
Plate ID	# 21		# 22		# 25		# 11		# 15		# 16		# 1		# 6		# 9	
1	1593	P	1637	P	1532	P	1584	P	1510	C	1467	C	1584	P	1597	C	1612	C
2	1685	P	1991	C	1681	C	1747	C	1420	P	1240	C	1625	P	1569	P	1464	C
3	1837	C	2054	C	1596	P	1733	C	1452	C	1276	P	1915	C	1612	P	1433	P
4	1788	P	1718	P	1625	C	1637	P	1408	P	1286	P	1814	P	1612	C	1451	C
5	1808	C	1853	P	1617	C	1704	C	1520	C	1347	P	1861	C	1556	P	1396	P
6	1801	C	1943	C	1554	C	1676	C	1401	P	1832	C	1847	C	1586	P	1437	C
7	1783	P	1874	C	1523	P	1608	P	1458	P	1501	P	1849	C	1633	C	1520	P
8	1775	C	1796	P	1622	C	1615	P	1456	C	1652	P	1856	C	1640	C	1619	C
9	1791	P	1828	C	1559	C					1457	P						
10					1518	C												
11					1524	C												
12					1556	P												
Plate ID	# 19		# 24		# 26		# 12		# 14		# 17		# 2		# 4		# 7	
1	1779	P	1812	P	1568	P	1660	P	1466	C	1673	C	1775	P	1594	P	1628	C
2	1861	P	1825	P	1564	P	1697	P	1436	P	2019	C	1771	C	1479	P	1458	C
3	1922	C	1852	P	1667	P	1710	P	1500	P	1683	C	1751	P	1487	P	1411	C
4	1852	C	1916	C	1801	P	1752	C	1482	P	1556	C	1899	C	1454	C	1369	C
5	1837	C	1876	P	1813	C	1715	P	1518	C	1599	P	1805	C	1645	P	1539	C
6	1791	P	1894	P	1788	P	1730	C	1506	P	1940	C	1639	C	1677	C	1238	C
7	1794	C	1931	C	1825	P	1681	P	1582	C	1854	P	1752	C	1674	C	1829	C
8	1761	C	1901	P	1853	C	1759	C	1564	P	1397	C	1686	C			1710	C
9	1730	P	1953	C	1899	P					1699	P						
10	1727	C			1905	P												
11					1852	P												
12					1853	P												
13					1945	C												
14					1928	C												
Plate ID	# 20		# 23				# 10		# 13		# 18		# 3		# 5		# 8	
1	1847	P	1852	C			1739	C	1472	P	1512	C	1750	P	1739	C	1628	C
2	1996	C	1916	C			1719	C	1572	P	1470	P	1927	C	1776	P	1401	C
3	1971	C	1805	C			1693	P	1618	C	1609	P	1841	C	1805	C	1278	C
4	1949	C	1724	P			1698	C	1548	C	1204	P	1786	C	1992	C	1495	C
5	1894	P	1792	P			1681	C	1552	P	1369	P	1749	C	1935	C		
6	1878	C	1798	P			1691	C	1576	C	1574	C	1727	C	2032	C		
7	1883	P	1805	C			1632	P	1468	C	1814	P	1646	C				
8	1847	P	1767	P			1623	C	1498	C	1470	P	1585	P				
9	1905	C	1811	P			1650	P	1445	P	1579	P	1605	P				
	Plate 19												1606	P				
1	1936	C																
2	1724	P																
3	1803	C																
Total		31		27		26		25		25		27		26		21		20

Table 2. Summary of Macrocomposite Velocity (ft/s) Data in Shot Sequence Order.

Shot #	Lab 1	Result	Lab 2	Result	Lab 3	Result	Lab 4	Result	Lab 5	Result	Lab 6	Result	Lab 7	Result	Lab 8	Result	Lab 9	Result
1	1589	P	1718	P	1608	C	1600	P	1566	P	1610	P	1512	P	1603	P	1635	P
2	1727	C	1899	C	1595	P	1652	C	1674	P	1545	P	1853	C	1689	C	2007	P
3	1655	P	1796	P	1588	P	1625	P	1727	P	1781	P	1801	C	1701	C	2384	P
4	1680	P	1893	P	1689	P	1670	P	1834	C	2058	C	1712	C	1653	P	2773	C
5	1716	P	1869	P	1708	P	1710	P	1781	P	1871	P	1519	P	1658	P	1765	C
6	1754	P	1853	P	1770	P	1714	C	1767	C	1881	C	1673	C	1711	C	1726	C
7	1732	P	2382	P	1786	C	1694	P	1743	C	1908	P	1533	P	1720	C	1668	P
8	1775	C	2698	C	1742	P	1727	C	1713	P	1927	C	1642	P	1676	P	1678	C
9	1744	C	1727	P	1789	P	1679	C	1737	P	1856	P	1676	C	1676	P	1682	P
10	1725	P	1772	C	1770	P	1654	P	1713	P	1993	C	1675	C	1714	P	1724	C
11	1785	P	1772	P	1898	C	1555	P	1803	C	1837	C	1619	P	1759	P	1674	P
12	1829	C	1684	P	2010	P	1754	P	1761	C	1846	C	1662	C	1805	C	1496	P
13	1814	C	1784	C	2027	P	1803	C	1432	P	1825	C	1658	P	1847	C	1637	P
14	2450	P	1800	C	2181	P	2000	C	1466	P	1802	C	1647	NT	1546	C	1733	C
15	2467	P	1802	C	1937	P	1943	P	2434	P	2179	P	1658	P	1874	P	1703	C
16	1906	P	1797	P	1813	P	1910	P	2432	P	2373	C	1591	P	1948	P	1675	P

Table 3. Velocity (ft/s) Delta for Steel Panels.

Shot #	Lab 1	Result	Lab 2	Result	Lab 3	Result	Lab 4	Result	Lab 5	Result	Lab 6	Result	Lab 7	Result	Lab 8	Result	Lab 9	Result
Start	1600	fps	1600	fps	1600	fps	1600	fps	1600	fps	1600	fps	1600	fps	1600	fps	1600	fps
Plate	# 21		# 22		# 25		# 11		# 15		# 16		# 1		# 6		# 9	
1	-7	P	37	P	-68	P	-17	P	-90	C	-133	C	-16	P	-3	C	12	C
2	92	P	354	C	149	C	164	C	-90	P	-227	C	41	P	-28	P	-148	C
3	152	C	63	C	-85	P	-14	C	32	C	36	P	290	C	43	P	-31	P
4	-49	P	-336	P	29	C	-96	P	-44	P	10	P	-101	P	0	C	18	C
5	20	C	135	P	-8	C	67	C	112	C	61	P	47	C	-56	P	-55	P
6	-7	C	90	C	-63	C	-28	C	-119	P	485	C	-14	C	30	P	41	C
7	-18	P	-69	C	-31	P	-69	P	57	P	-331	P	2	C	46	C	83	P
8	-8	C	-78	P	99	C	7	P	-2	C	151	P	7	C	7	C	99	C
9	16	P	32	C	-63	C					-195	P						
10					-41	C												
11					6	C												
12					32	P												
Plate	# 19		# 24		# 26		# 12		# 14		# 17		# 2		# 4		# 7	
1	-12	P	-16	P	12	P	46	P	10	C	216	C	-81	P	-46	P	9	C
2	82	P	13	P	-4	P	37	P	-30	P	346	C	-4	C	-115	P	-170	C
3	61	C	27	P	103	P	13	P	64	P	-336	C	-20	P	8	P	-47	C
4	-70	C	64	C	134	P	42	C	-18	P	-127	C	148	C	-33	C	-42	C
5	-15	C	-40	P	12	C	-37	P	36	C	43	P	-94	C	191	P	170	C
6	-46	P	18	P	-25	P	15	C	-12	P	341	C	-166	C	32	C	-301	C
7	3	C	37	C	37	P	-49	P	76	C	-86	P	113	C	-3	C	591	C
8	-33	C	-30	P	28	C	78	C	-18	P	-457	C	-66	C			-119	C
9	-31	P	52	C	46	P					302	P						
10	-3	C			6	P												
11					-53	P												
12					1	P												
13					92	C												
14					-17	C												
Plate	# 20		# 23				# 10		# 13		# 18		# 3		# 5		# 8	
1	120	P	-101	C			-20	C	-92	P	-187	C	65	P	65	C	-82	C
2	149	C	64	C			-20	C	100	P	-42	P	177	C	37	P	-227	C
3	-25	C	-111	C			-26	P	46	C	139	P	-86	C	29	C	-123	C
4	-22	C	-81	P			5	C	-70	C	-405	P	-55	C	187	C	217	C
5	-55	P	68	P			-17	C	4	P	165	P	-37	C	-57	C		
6	-16	C	6	P			10	C	24	C	205	C	-22	C	97	C		
7	5	P	7	C			-60	P	-108	C	240	P	-82	C				
8	-36	P	-38	P			-9	C	30	C	-344	P	-61	P				
9	58	C	-44	P			27	P	-53	P	109	P	20	P				
Plate	# 19												2	P				
1	31	C																
2	-212	P																
3	79	C																
Total		31		27		26		25		25		27		26		21		20

Table 4. Velocity (ft/s) Delta for Macrocomposite Panels.

Shot #	Lab 1	Result	Lab 2	Result	Lab 3	Result	Lab 4	Result	Lab 5	Result	Lab 6	Result	Lab 7	Result	Lab 8	Result	Lab 9	Result
Start	1600	fps	1600	fps	1600	fps	1600	fps	1600	fps	1600	fps	1600	fps	1600	fps	1600	fps
1	-11	P	118	P	8	C	0	P	-34	P	10	P	-88	P	3	P	35	P
2	138	C	180	C	-13	P	52	C	108	P	-65	P	341	C	86	C	372	P
3	-72	P	-102	P	-7	P	-28	P	53	P	236	P	-52	C	11	C	378	P
4	25	P	97	P	101	P	45	P	107	C	277	C	-89	C	-48	P	389	C
5	36	P	-24	P	19	P	40	P	-53	P	-187	P	-193	P	5	P	-1008	C
6	38	P	-16	P	62	P	4	C	-14	C	10	C	154	C	53	C	-39	C
7	-22	P	529	P	16	C	-20	P	-24	C	27	P	-140	P	9	C	-58	P
8	43	C	316	C	-44	P	33	C	-30	P	19	C	109	P	-44	P	10	C
9	-31	C	-971	P	47	P	-48	C	24	P	-71	P	34	C	0	P	4	P
10	-19	P	44	C	-19	P	-25	P	-24	P	137	C	-1	C	38	P	42	C
11	60	P	0	P	128	C	-99	P	90	C	-156	C	-56	P	45	P	-50	P
12	44	C	-87	P	112	P	199	P	-42	C	9	C	43	C	45	C	-178	P
13	-15	C	100	C	17	P	49	C	-329	P	-21	C	-4	P	43	C	141	P
14	636	P	16	C	154	P	197	C	34	P	-23	C	-11	NT	-301	C	96	C
15	17	P	2	C	-244	P	-57	P	968	P	377	P	11	P	328	P	-30	C
16	-561	P	-5	P	-124	P	-33	P	-2	P	194	C	-67	P	74	P	-28	P

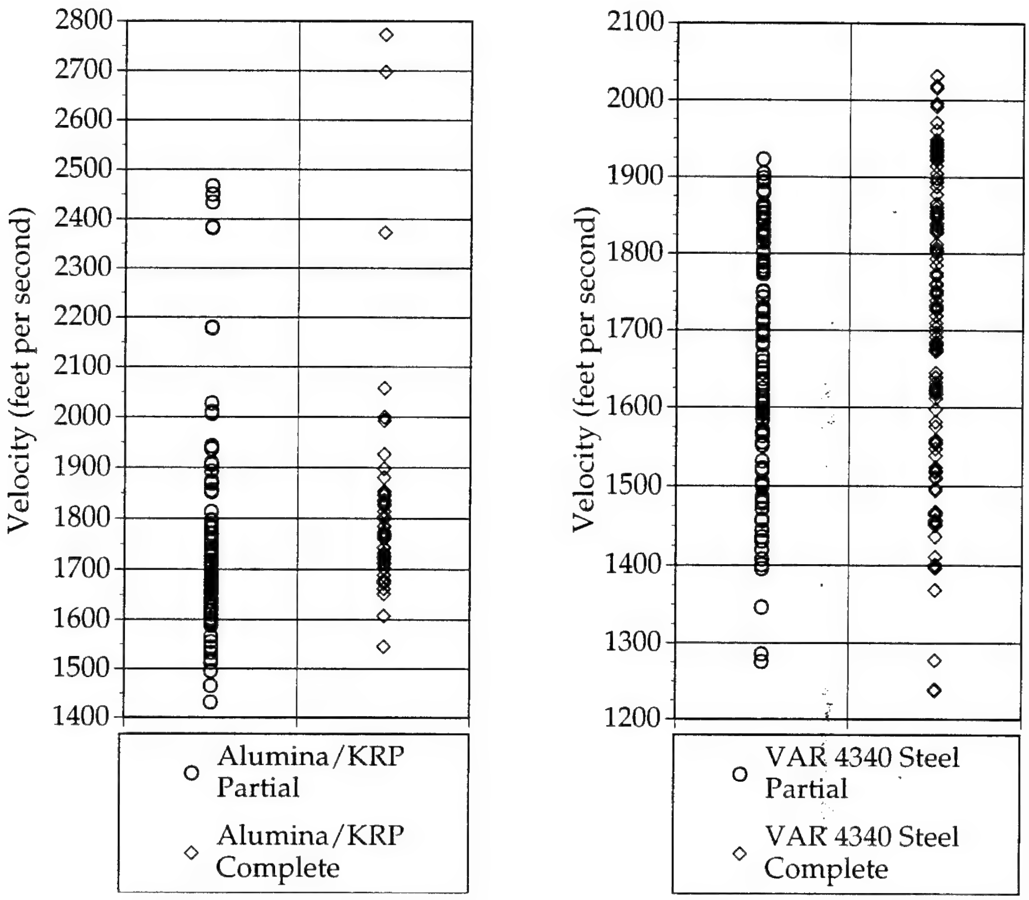


Figure 3: Grand Summary of Partial Penetration and Complete Penetration Data.

Analysis

Our analysis of the interlaboratory data is intended to determine whether the results of ballistic testing at various test facilities are reproducible. We did not try to quantify parameters such as bias because this requires comparison to a value accepted as "true". Based on our initial review of the data, there was no compelling basis for identifying any laboratory's result as being the "true" V_{50} value. Indeed, at the completion of the testing sequence, each laboratory expressed confidence that they had indeed determined the "true" V_{50} value.

For a test method to be determined reproducible, it must be possible to have the test performed on the same material, at various facilities, and achieve results that are not statistically different with a reasonable confidence level. We minimized or eliminated many material variables inherent in the conduct of a ballistic test by providing each lab with statistically identical target panels and 0.50 caliber AP M2 projectiles. We instructed the laboratories to conduct the ballistic test in accordance with MIL-STD-662E.

The Project Manager made no attempt to control each laboratory's test fixtures, velocity measuring equipment, environmental conditions or, most significantly, V_{50} calculation methods. We assumed that any variations in the test results were attributable to these

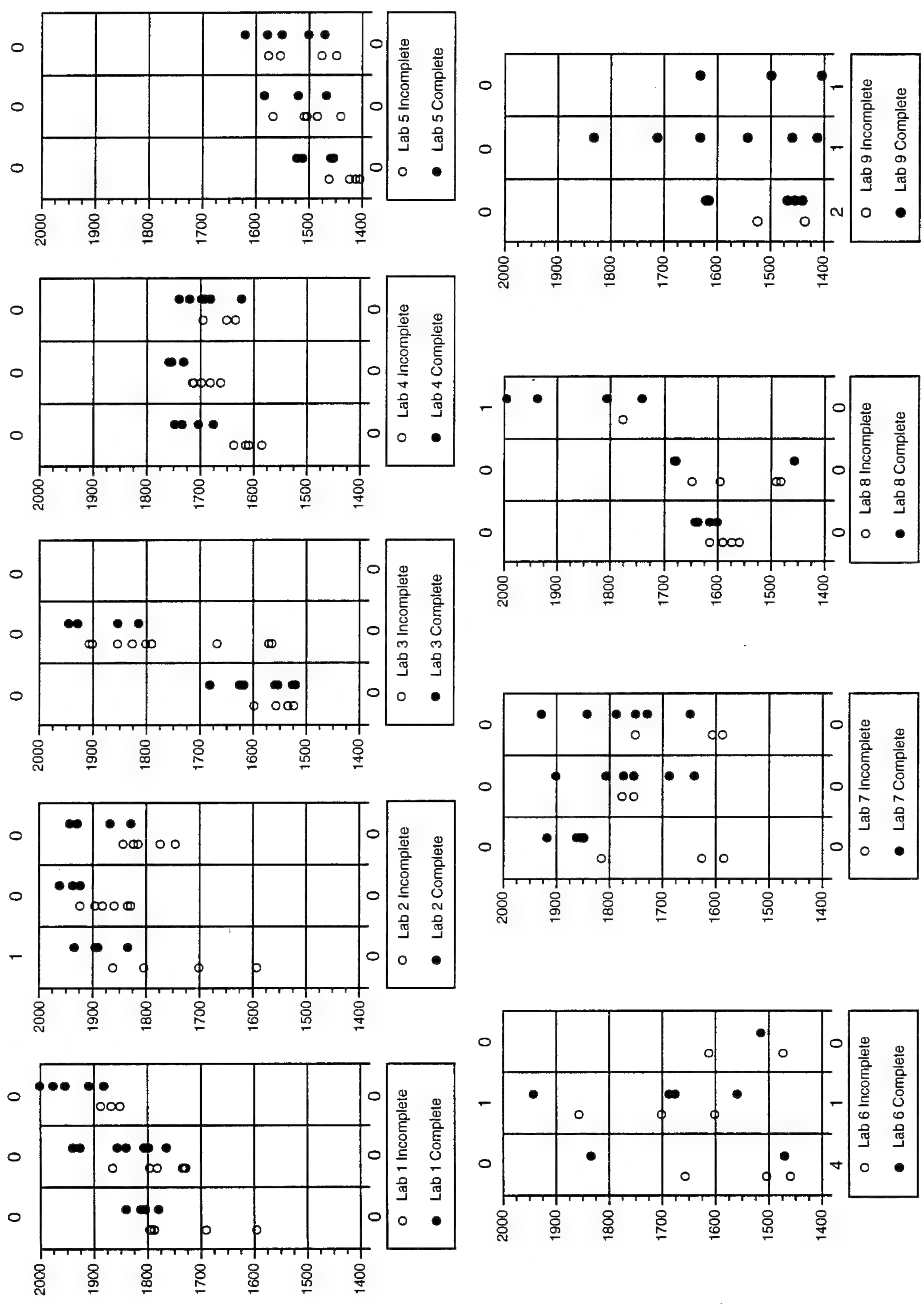


Figure 4: Graphical Representation of Data for the Steel Panels.

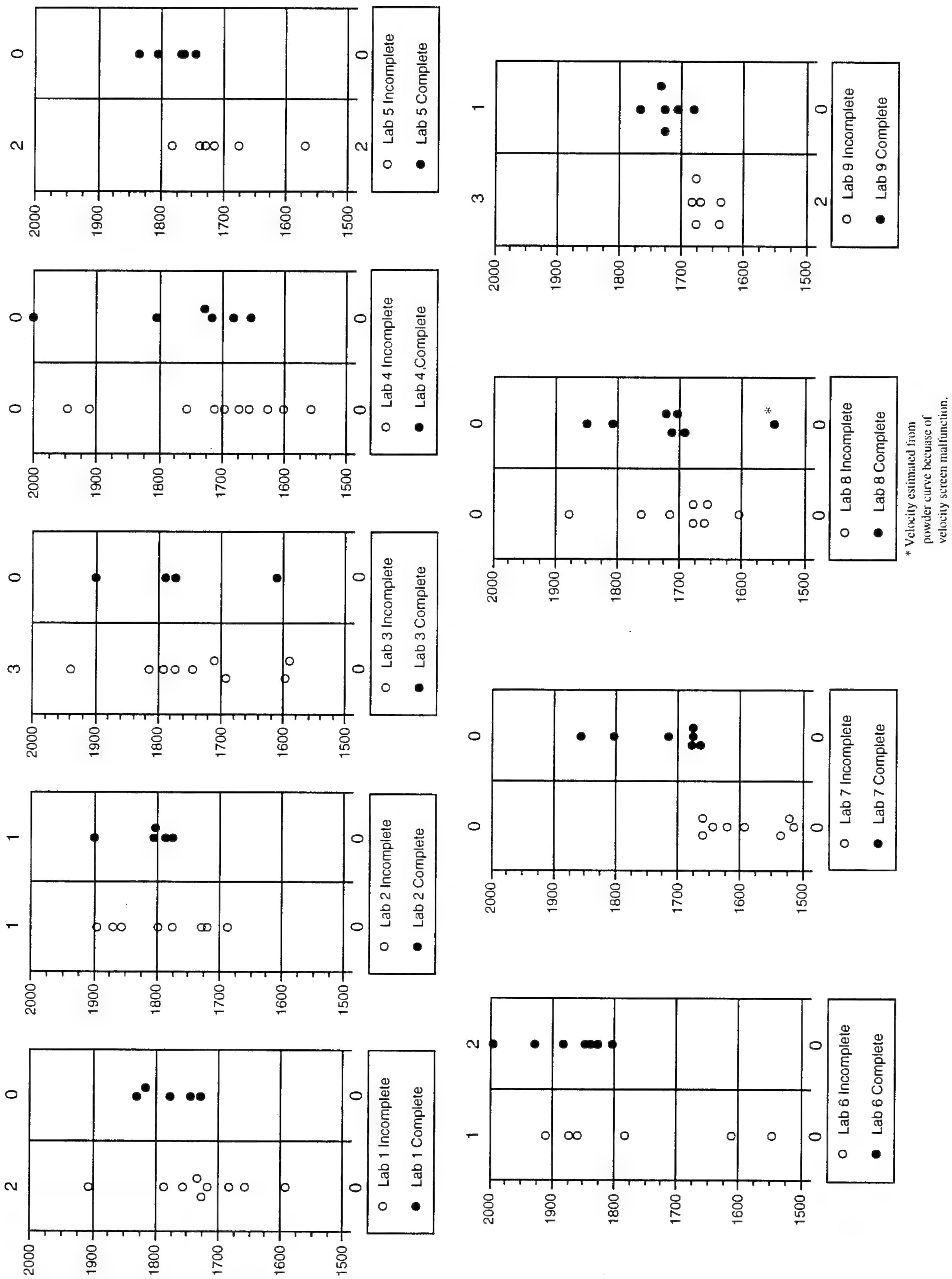


Figure 5: Graphical Representation of Data for the Macrocomposite Panels.

variables. We conjecture that the most significant source of variability results from the method used to select shot velocities and thus calculate the V_{50} value. Most laboratories rely upon experience and intuition when selecting velocities. Although most laboratories used variants of the up & down method for velocity selection, none of them applied a single velocity selection algorithm uniformly. We will use our analysis of the test data to draw conclusions about the suitability of such heuristic test methods, in combination with any non-standardized fixturing hardware.

We focused our attention on the laboratory reports, searching for an acceptable method for comparing the results. The reports returned from the laboratories participating in the interlaboratory study included raw firing data, and in most cases a reported V_{50} value. They differed in format and completeness. Some laboratories reported separate V_{50} values for each steel panel. Others reported one V_{50} value, calculated using the shots against all of the three steel panels, collectively. Some laboratories reported a V_{50} value based on the average of the V_{50} values obtained from each respective panel.

Deciding upon a method to compare the results obtained from each lab is nontrivial due to the variation in the reports and the method employed to calculate a V_{50} value. The laboratories reported the firing sequence, velocity and test result, for each test shot, uniformly well. Consequently, it appears reasonable to use these elements of the raw data to recalculate V_{50} values using a standard procedure. We chose to recalculate the V_{50} values strictly using Test Operations Procedure (TOP) 2-2-710 procedures.

TOP 2-2-710, *Ballistic Tests of Armor Materials*, describes several different methods for calculating a V_{50} value.[9] Each method is characterized by the number of partial and complete penetrations and the maximum velocity range encompassing the data points used to calculate the V_{50} value. Some of the methods are listed in Table 5.

The first four methods are based on up & down velocity selection. The first round is prepared to yield a firing velocity nearly equal to the expected V_{50} value. The second

Table 5: V_{50} Calculation Methods and Velocity Ranges.

V50 Type	Velocity Range	Assumed Distribution Type
1 partial & 1 complete	15 m/s (50 fps)	Normal
2 partials & 2 completes	18 m/s (60 fps)	Normal
3 partials & 3 completes	27, 38, or 46 m/s (90, 125, 150 fps)	Normal
5 partials & 5 completes	38, 46 m/s, or unlimited (125, 150 fps)	Normal
Langlie (12 rounds)	not stipulated	Normal
Sampling-of-Levels	single fixed velocity	Not Normal
Probit Design	several fixed velocities	Normal

round is prepared to yield a firing velocity ±100 fps relative to first round. If the result of the first round results in penetration of the target, the lower velocity is used; if the round failed to penetrate the target, the higher velocity is used. Subsequent rounds are prepared ±100 fps for same result or ±50 fps for a reversal. After the first reversal, subsequent rounds are prepared ±50 fps for same result or ±25 fps for an additional reversal. Note that the Langlie Method requires application of the method of maximum likelihood for data reduction.

We organized the firing data from each lab in the order the shots were taken. A V_{50} value was calculated considering each successive shot in the following manner:

(1) When one partial penetration (PP) and one complete penetration (CP) result within a maximum velocity spread of 50 fps, the arithmetic mean of the two velocities is reported as the V_{50} value. The velocity spread is calculated by subtracting the lowest velocity of the two shots from the higher velocity in the sample.

(2) When two PPs and two CPs result within a maximum velocity spread of 60 fps, the arithmetic mean of the four velocities is reported as the V_{50} value. The velocity spread is calculated by subtracting the lowest velocity in the sample from the highest velocity in the sample.

(3) When three PPs and three CPs result within a maximum velocity spread of 150 fps, the arithmetic mean of the six velocities is reported as the V_{50} value. The velocity spread is calculated by subtracting the lowest velocity in the sample from the highest velocity in the sample.

(4) When five PPs and five CPs result, the arithmetic mean of the ten velocities is reported as the V_{50} value. The velocity spread is calculated by subtracting the lowest velocity in the sample from the highest velocity in the sample.

Table 6 lists the V_{50} values calculated as described above, for the steel panels. Table 7 contains similar information for the macrocomposite panels. The tables also present the V_{50} values reported by each laboratory. Having calculated the V_{50} values using a single, uniform methodology, we can now proceed to compare the results obtained from each lab using statistical analysis. Recalculating the data is an important step. We needed to normalize the data to establish a uniform basis for statistical comparison. Using this approach, excessive variation in the V_{50} values can be attributed to a combination of the velocity selection heuristic, and the test hardware used.

The data in each row of Tables 6 and 7 can be compared using a variety of statistical comparison techniques. One particularly well documented comparison method is the Tukey Method. The Tukey method conducts pairwise comparisons of n sample means to establish whether $\mu_i = \mu_j$, for $i, j = 1 \ldots n$, at a selected level of confidence. We can use the Tukey Method to conduct multiple pairwise comparisons of the recalculated V_{50} values displayed in Tables 6 and 7. The method allows the analyst to select a confidence level at which to compare the means from various samples of equal size. In our case the means in question are the V_{50} values. When the sample sizes producing the means are equal and all

Table 6: Table of V_{50} Values for Steel Panels.

V_{50} Type	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Lab 6	Lab 7	Lab 8	Lab 9
1 & 1 in 50 fps	1813	1820	1807	1657	1595	1258	1838	1583	1449
2 & 2 in 60 fps	1795	1852	1823	1684	1562	1677	1791	1598	1429
3 & 3 in 150 fps	1773	1850	1878	1657	1556	1644	1794	1602	1450
5 & 5	1815	1834	NC*	1693	1503	1514	1746	1585	NC*
Reported	1819	1876	1867	1683	1497	1520	1716	1602	1429

Table 7: Table of V_{50} Values for Macrocomposite Panels.

V_{50} Type	Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Lab 6	Lab 7	Lab 8	Lab 9
1 & 1 in 50 fps	1704	1896	1601	1638	1774	1876	1658	1671	1673
2 & 2 in 60 fps	1747	1781	1772	1684	1755	1897	1652	1675	1689
3 & 3 in 150 fps	1741	1845	1804	1695	1761	1906	1634	1669	1692
5 & 5	1760	1975	NC*	1706	1758	1872	1657	1711	1908
Reported	1760	1814	1790	1694	1758	1841	1657	1708	1692

* NC stands for Not Calculated, indicating insufficient data to calculate the V_{50} value.

pairwise comparisons are to be made, the Tukey method is preferred over other comparison techniques because it yields the narrowest confidence intervals.[21] The entries in each respective row of Tables 6 and 7--except the reported V_{50} row)--are the result of the arithmetic mean of equal sized samples.

We selected several confidence levels for use in our analysis. The confidence levels we selected include 0.01 (99%), 0.05 (95%), 0.10 (90%), 0.15 (85%) and 0.25 (75%). Lowering the confidence level increases the likelihood of rejecting the hypothesis that $\mu_i = \mu_j$. In other words, we presume initially that the mean (V_{50}) values are equal. We want a certain level of confidence in our determination of any inequalities. At lower confidence levels, we expect more pairwise comparisons to result in a determination of significant difference because the difference between the two means being considered need not be as great to arrive at the conclusion that they are unequal. At higher confidence levels fewer differences are detected, but those detected are more significantly different. We used a broad spectrum of confidence levels to demonstrate that even at high levels of confidence a substantial percentage of significant differences exists between the V_{50} values from the interlaboratory test data.

We selected *MINITAB* a widely available statistical software package, to aid in the analysis because it performs the Tukey-Method calculations quickly and provides the output in an easily understood manner.[22] For example, the data in row 1 of Table 6 gives V_{50} values calculated using one partial and one complete penetration within a velocity range of 50 fps, for each lab. Consequently, the sample size for each V_{50} value is two. *MINITAB* was used to do the Tukey analysis at the 0.05 (95%) confidence level. Figure 6 displays the resulting output. Each cell in the Table of Pairwise Comparisons represents a range of values that bounds the possible difference between the V_{50} value from lab_i and lab_j at the

Figure 6: Table of Pairwise Comparisons, Minitab Output for 0.05 Confidence Level

LAB	1	2	3	4	5	6	7	8
2	-158.9 43.9							
3	-95.9 106.9	-38.4 164.4						
4	*54.6* *257.4*	*112.1* *314.9*	*49.1* *251.9*					
5	*116.1* *318.9*	*173.6* *376.4*	*110.6* *313.4*	-39.9 162.9				
6	*453.1* *655.9*	*510.6* *713.4*	*447.6* *650.4*	*297.1* *499.9*	*235.6* *438.4*			
7	-126.4 76.4	-68.9 133.9	-131.9 70.9	*-282.4* *-79.6*	*-343.9* *-141.1*	*-680.9* *-478.1*		
8	*127.6* *330.4*	*185.1* *387.9*	*122.1* *324.9*	-28.4 174.4	-89.9 112.9	*-426.9* *-224.1*	*152.6* *355.4*	
9	*262.6* *465.4*	*320.1* *522.9*	*257.1* *459.9*	*106.6* *309.4*	45.1 247.9	-291.9 -89.1	*287.6* *490.4*	*33.6* *236.4*

Example: The difference between the V50 reported by lab3 and lab4 is between 49 and 252 with 95% confidence. The range does not include zero, so the two V50's are statistically different.

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.00336

0.05 confidence level. If the interval does not contain zero there is a significant statistical difference between the two V_{50} values from the laboratories being compared. Italicized entries in the table indicate cells where a significant difference exists. We can use the same procedure to compare the data in each row of Table 6 and Table 7 at the significance levels we selected. We performed a Tukey analysis for each type of V_{50} value and each of the two panel materials. The Appendix includes the results of these analyses at the 0.05 confidendce level in the following tables:

Table A1: Steel V_{50} Values (1 PP, 1 CP) In 50 fps
Table A2: Steel V_{50} Values (2 PP, 2 CP) In 60 fps
Table A3: Steel V_{50} Values (3 PP, 3 CP) In 150 fps
Table A4: Steel V_{50} Values (5 PP, 5 CP)
Table A5: Steel V_{50} Values (1 PP, 1 CP) In 50 fps
Table A6: Ceramic V_{50} Values (2 PP, 2 CP) In 60 fps
Table A7: Ceramic V_{50} Values (3 PP, 3 CP) In 150 fps
Table A8: Ceramic V_{50} Values (5 PP, 5 CP)

The total number of pairwise comparisons possible using the standardized data in Tables 6 and 7 is 265. The results of our Tukey analyses are given in the Table 8.

At the 0.01 (99%) confidence level, 149 of the 265 possible pairwise comparisons are found to have a significant statistical difference. Restated, the Tukey analysis indicates that 56% of all pairwise comparisons of lab V_{50} values show a significant statistical difference at our most discriminating level of significance.

Table 8: Results of Tukey Analysis for Five Levels of Confidence

Confidence Level (%)	Significant Differences	Percent of total Comparisons (%)
99	149	56
95	162	61
90	169	64
85	172	65
75	181	68

In presenting the Tukey analysis, we must keep in mind that "there is more controversy among statisticians regarding which multiple comparisons procedure to use when sample sizes are unequal than when sample sizes are equal." The method recommended in *Beyond ANOVA: Basics of Applied Statistics*[23] is a modified Tukey method used when sample sizes vary, but are 'reasonably close'. The entries in the reported V_{50} row in each table represent the arithmetic mean of *un*equal sample sizes. Unfortunately, sample sizes varied from 4 to 22, and in some cases were not reported at all! Consequently, the Modified Tukey method may not be an acceptable comparison technique for this data.[24]

In addition to the Tukey analysis, we also applied a modified Kruskal - Wallis (KW) analysis. Like the Tukey analysis, the KW analysis assumes that the samples are randomly and independently selected. Unlike the Tukey analysis, the KW analysis does not assume an underlying distribution. However, it requires at least five data points, which precludes consideration of all sets of 1 & 1 (two data points) and 2 & 2 (four data points) V_{50} values.

The result of the KW analysis is a test statistic K, which is defined as follows:

$$K = \frac{12}{n\,(n+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3\,(n+1) \tag{4}$$

This test statistic is used to determine if one laboratory is statistically different from the other laboratories as a group. This is an important difference from the Tukey analysis which permits one to one comparison between the laboratories. The results of this analysis are shown in Table 9. These K values are then compared to those in Table 10 for the appropriate confidence level and degrees of freedom. The degrees of freedom is simply the number of laboratories less one. Although the KW analysis method requires fewer underlying assumptions and only provides comparison of each laboratory to the group, the results lead us to the same conclusion as the Tukey analysis, namely that each individual laboratory cannot be compared statistically to the other laboratories as a group.

We can also gain some insight into the reported V_{50} values by examining some descriptive statistics obtained from each laboratory. As a measure of data dispersion and variability, we choose the standard deviation and range, which are displayed in Table 11. For our purposes, the range was calculated by subtracting the highest V_{50} value from the lowest

Table 9: Results of Kruskal - Wallis Analysis

Panel Type	Test Type	K value	Degrees of Freedom
Macrocomposite	3 and 3	44.97	8
Macrocomposite	5 and 5	43.05	7
Steel	3 and 3	48.17	8
Steel	5 and 5	47.15	6

Table 10: K Values as a Function of Confidence Level and Degrees of Freedom.

Confidence Level	Degrees of Freedom		
	6	7	8
90%	K > 10.64	K > 12.16	K > 13.36
95%	K > 12.59	K > 14.07	K > 15.50
99%	K > 16.81	K > 18.47	K > 20.90

V_{50} value for each type of target panel. The range and standard deviation of the data for the steel are most noteworthy. Although a certain degree of stochastic behavior is expected, the range of the steel V_{50} values is 27% of the mean and the standard deviation is 10% of the mean. Measures of such magnitude indicate a high level of variability and dispersion in the reported V_{50} values. Although the statistics for the macrocomposite panels are not as dramatic, we conclude that there is sufficient variability to question site-to-site reproducibility of the tests, irrespective of the material. Note that it is possible to find two or three laboratories where the interlaboratory agreement is very good. If only these two or three laboratories had been selected to participate in this study, a completely different conclusion would be in order. This fact vividly illustrates the necessity for widespread participation in any interlaboratory test series.

Discussion

Heuristics and experience play key roles in many fields of science, but clearly their presence effects the value of the calculated V_{50} Ballistic Protection Limit (PBL). The intuition of the test engineer influences velocity selection and hence introduces bias into the outcome of the test. This concept is best illustrated by considering the shot sequence data of Tables 1 and 2 in a graphical format, as displayed in Figure 7 for the steel data and Figure 8 for the macrocomposite data. For most of the laboratories, once the test engineer obtained a reversal—a change in test result from the previous test shot—he confined his attention to

Table 11: Descriptive Statistics

Statistic	Steel V_{50} Value (fps)	Macrocomposite V_{50} Value (fps)
Mean	1668	1746
Standard Deviation	166	62.2
Std. Dev. as a percentage of Mean	10%	4%
Range	447	183
Range as a percentage of Mean	27%	11%

a relatively narrow velocity range. This may explain why there is usually very little difference between the 1 & 1 V_{50} value and the 3 & 3 V_{50} value. For the steel panels, all but one laboratory (Laboratory 6) produced a 1 & 1 V_{50} value within 100 fps of the 5 & 5 V_{50} value. For the macrocomposite panels, three laboratories (Laboratories 2, 3, and 9) produced data sets with wide discrepancy between different types of V_{50} values. Only when more data points are forced into the calculation with the 5 & 5 V_{50} value is there appreciable change in the apparent protection ballistic limit.

This may be due, in part, to overreliance on the up & down velocity selection recommended by both MIL-STD 662E and TOP 2-2-710. As a point of information, we compiled information from Tables 3 and 4 presented in the Results section, to ascertain how often the test engineers adjusted the velocity in increments of greater than 100 fps. Table 12 shows the results of this analysis. This table confirms that most test engineers complied with up & down shooting with modest (< 100 fps) increments for most of the test sequence. There are, however two notable exceptions. Laboratory 6 used velocity changes in excess of 100 fps 65% of the time. Laboratory 9 was a distant second with 42% of velocity changes in excess of 100 fps. For the macrocomposite panels, Laboratory 9 bypassed the lower V_{50} value for the macrocomposite panels by using a 400 fps delta to adjust velocity from one firing to the next. Although this may seem like a large delta, it is acceptable under both MIL-STD-662E and TOP 2-2-710.

It is interesting to note that Laboratories 6 and 9 were the only two laboratories that reported large numbers of complete penetrations below 1400 fps for the steel panels. Rather than treat these points as anomalous, the fact that two independent laboratories obtained this result forces us to consider the possibility that these data are a real manifestation of this material's behavior, a possible transition in failure phenomenon at low impact velocities. Here again, if just one of these two laboratories had not participated in the study our outlook on this data would be much different.

A possible explanation for the scatter in the steel data may be a manifestation of a *shatter gap*. The steel panels used for this study had a hardness of approximately 50-52 HRC; the projectiles, a hardness of approximately 61 HRC. The purpose of the high hardness steel is to fracture the impacting projectile prior to penetration of the target. If the panel is not hard enough, the intact projectile can easily defeat the panel through a plugging mechanism.

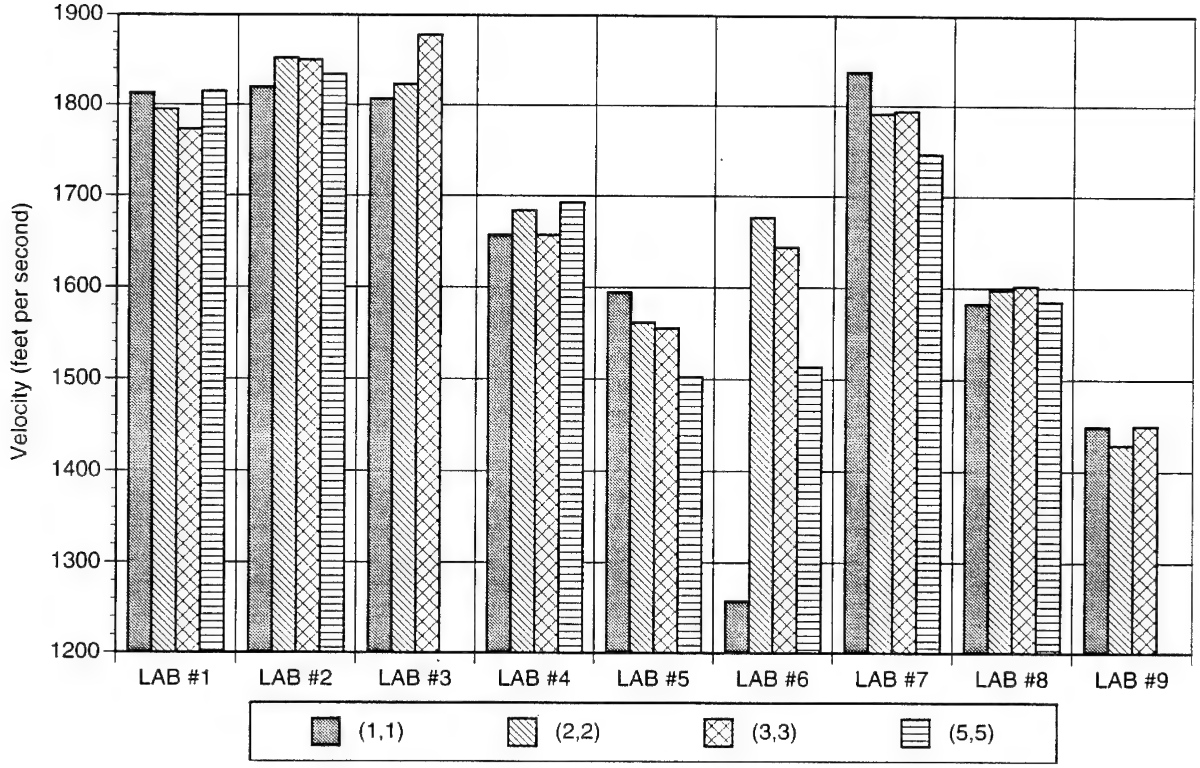


Figure 7. Recalculated V_{50} Values for Steel Panels.

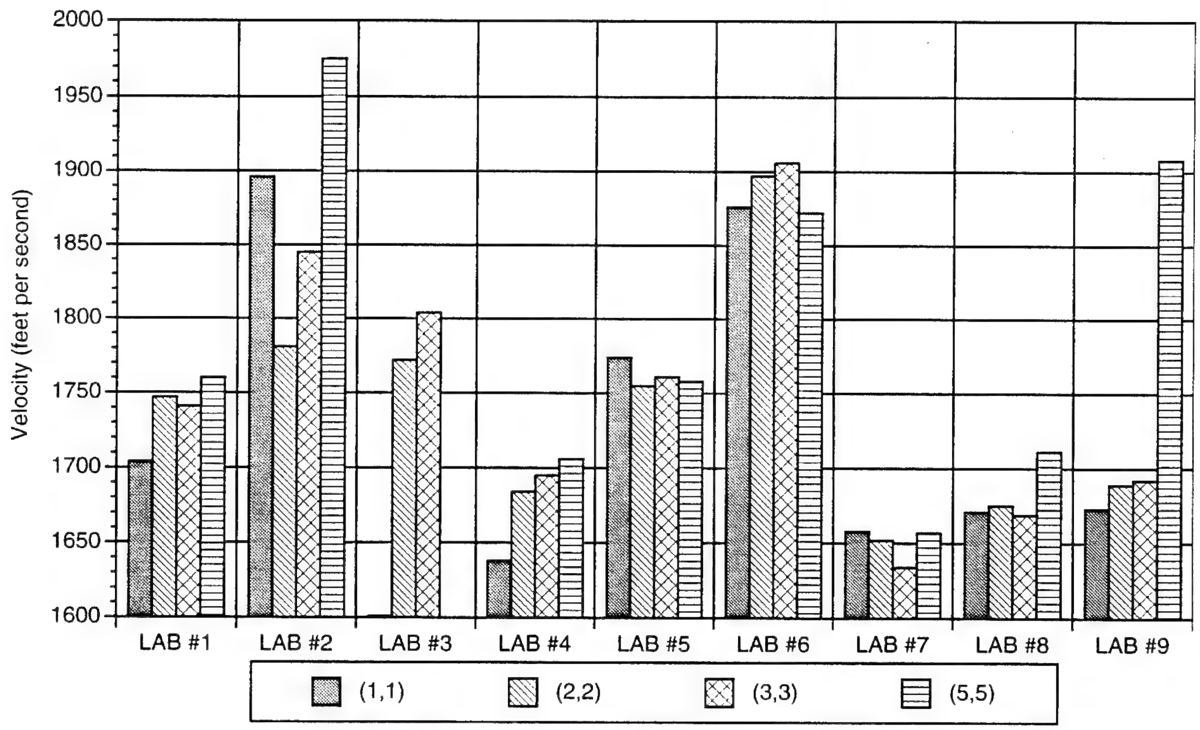


Figure 8. Recalculated V_{50} Values for Macrocomposite Panels

Table 12: Velocity Delta Statistics

Statistic	Steel Panels	Macrocomposite Panels
Total Shots	228	143
Shots with delta velocity > 100 fps	55	41
As a percentage	24%	29%

Some laboratories observed that surface hardness on some of the steel panels fell below the expected range of 48 - 52 HRC. A uniformly low cross sectional hardness would certainly explain low penetration velocities for the steel panels. To determine if this was a plausible explanation, microhardness measurements were taken on the cross section of some of the panels.

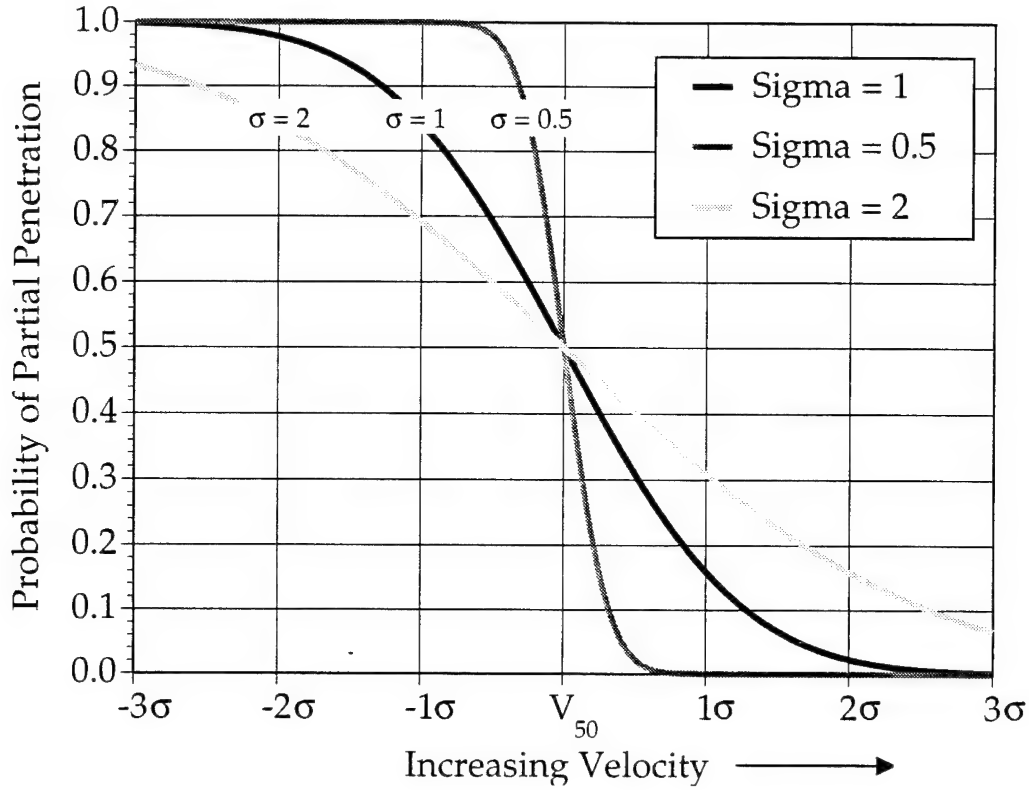
These measurements quantified the maximum decarburized layer at 0.015 inch. This raises the question: can a 0.015 inch thick soft surface layer result in a severe performance drop of 300 fps in an armor steel? Although this question has not been studied in detail, research conducted at ARL•MD did show that removing a 0.05 inch layer of decarburization resulted in dramatic improvement--almost a factor of two--in a ballistic test.[25] Although variable levels of decarburization may have contributed to the zone of mixed results, by itself it does not appear sufficient to explain the magnitude of that zone.

Since ballistic testing of materials is intended primarily for use in armor design, a few observations regarding armor design are in order. Historically, lightweight armor has been designed to meet a particular V_{50} value.[26] Therefore, at the design velocity (V_{50} value), there is a 50% probability that either the specified design projectile or fragments will cause damage to components or inflict lethal or serious injury to personnel. Although this is a good first approach to armor design, the probability of survival is still only 50%. There is a potential pitfall when evaluating materials strictly based on the V_{50} value alone.

For design purposes, a material's distribution function is far more important than the V_{50} value. Consider Figure 9, which shows CDF curves for three different normal distributions. Although the associated theoretical armor materials have equivalent V_{50} values, they do not provide equivalent ballistic protection because each material has a different standard deviation about the V_{50} value.

A more reasoned approach to armor design should involve a much higher probability of survival, in excess of 90%. To use this approach, a designer must know more about the cumulative distribution function which describes the armor performance as a function of velocity. Given the resources to generate sufficient data, the distribution function can be determined by recursive modeling techniques. The difficulty with this approach is that the number of individual shots required to demonstrate a high survival rate within an acceptable confidence level is a function of the CDF. In other words, there is no statistical basis for standardizing the number of test shots required to adequately determine a CDF suitable for design purposes.

Figure 9. Graph Showing Three Normal Cumulative Distribution Functions with



From the standpoint of a statistically reliable test design too few panels were used during this study. In addition, none of the variables reported are truly independent. However, the number of panels used for this study was far in excess of that normally tested to establish a V_{50} PBL. In fact, the number of panels used for these tests was between two and four times greater than a typical compliment of panels. To apply traditional statistical methods, the number of data points required is usually greater than thirty (30), a twofold increase over the number of shots traditionally used for these tests. The net impact of requiring more than thirty shots for determination of a V_{50} value would be a materials cost increase of between four (4) and eight (8) times existing costs and commensurate cost increases for ballistic testing. Moreover, the existing MIL-STD-662E and TOP 2-2-710 provide the test engineer with a great deal of latitude in *selecting* the sequence of firing velocities.

Prior to drawing final conclusions based on this statistical analysis, we must reconsider our original assumptions:

(1) the target panels have identical microstructures and physical properties,

(2) the AP M2 projectiles are essentially identical,

(3) any excessive variation in the test results can be attributed to subjective test methodology.

Since all the steel panels and similarly all the ceramic composite panels were each fabricated at one facility, undergoing the same processing treatments, we believe assumption one remains valid within some negligible tolerance range. A similar argument holds true for

the projectiles. Assumption three states that any 'large' variation must result from differences in the test methodology used. Specifically, the variance introduced by using different, subjective velocity selection procedures and test hardware (including systematic differences in fixtures, distance and time measuring equipment, environmental conditions, and human error) additively combine to form the overall variance in the result. We continue to support the assumption that any large variations in test results observed during these interlaboratory tests is a result of non-standardized test methodology, specifically the absence of conventional testing protocols and test hardware configurations.

The Tukey and Kruskal - Wallis analyses were both used to compare the standardized V_{50} values. Both of these analyses and the descriptive statistics, calculated to compare the reported V_{50} values, indicate that the test results obtained from the laboratories are not reproducible. The analysis produced the same result regardless of the type of V_{50} value considered. Existing statistical differences exceed those that are reasonably expected to occur as a result of any small variations in the panels or projectiles. We surmise that ballistic tests conducted in accordance with MIL-STD-662E are not reproducible because of the different test methodologies and test hardware indigenous to each participating laboratory.

It is critical to note that the test methodologies in question include:

(1) the subjective method used to select firing velocities, and
(2) the configuration of test hardware including fixtures.

These variables were under the control of each laboratory within the guidelines of MIL-STD-662E. Each laboratory participating in the interlaboratory study conducted their ballistic tests in accordance with MIL-STD-662E, as witnessed by the Project Manager. Bearing these facts in mind, we find it reasonable to conclude that unacceptably high variations in the test results, which show that the tests are not reproducible, indicates that the latitudes provided by the test standards outlined in MIL-STD-662E can only be overcome with improvements to ballistic testing specifications.

It is interesting to note that the current version of MIL-STD-662, the E version, has less demanding requirements for calculating a V_{50} value than some previous versions. Table 13 includes a listing of each version of the standard together with the requirements for calculating a V_{50} value. In particular, note that versions A, B, and C required 10 impacts as a minimum. In addition, standard B specified that a zone of mixed results in excess of 150 fps required additional data (shots) to further elucidate the behavior of the armor material. Although the number of shots implicit in this requirement may seem excessive to those well practiced in the art of ballistic testing, the results obtained from this study indicate that even five partial penetrations and five complete penetrations are not sufficient to guarantee reproducibility of interlaboratory test results. Based upon the data obtained during the interlaboratory tests and our analysis of that data, we present the following conclusions and recommendations:

Conclusions

1. All of the laboratories calculated V_{50} values according to MIL-STD-662E, TOP 2-2-710, or both.
2. Using a 95% confidence level, ballistic test results are *not* reproducible from one laboratory to the next for both steel and macrocomposite panels.
3. Reducing the confidence level by increments of 5%, 10%, or 15% (to 90%, 85%, or 80%) does not alter the foregoing conclusion.
4. MIL-STD-662E does not effect reproducible ballistic test results for the materials studied: the procedures set forth in the standard need to be revised to make interlaboratory ballistic data reproducible.

Recommendations

1. Establish stricter rules for velocity selection, perhaps by using a velocity selection algorithm. This would help to eliminate subjective bias.
2. Standardize specimen test sizes and fixturing requirements.
3. Increase the minimum number of shots required to calculate a V_{50} value. Older versions of MIL-STD-662E required five partial penetrations and five complete penetrations to calculate a valid V_{50} value.
4. Establish a technical committee through a national, not-for-profit organization such as the American Society for Testing and Materials (ASTM) to tighten specifications, ensure statistical confidence, choose velocity selection algorithms, and measure reproducibility. By virtue of forming under ASTM, the committee would be open to membership from Government, Academia, and Industry.

Table 13: Chronology of MIL-STD-662.

Version Date	Title	Custodian	Witness Plate	Impacts	Partial Penetrations	Complete Penetrations	Maximum Velocity Range (feet per second)
MIL-STD-662 28 June 1961	Ballistic Acceptance Test Method for Personal Armor Material	Marine Corps	*	*	*	*	*
MIL-STD-662A 15 June 1964	Ballistic Acceptance Test Method for Personal Armor Material	Marine Corps	0.020" thick 2024-T3 aluminum	10	5	5	125
	Alternate Requirement		same	14	7	7	unlimited
MIL-STD-662B 23 July 1971	Ballistic Acceptance Test Method for Personal Armor Material	Marine Corps	0.020" thick 2024-T3 or T4 aluminum	10	5	5	125
	Alternate Requirement		same	14	7	7	150
MIL-STD-662C 23 October 1978	Ballistic Acceptance Test Method for Personal Armor Material	Army Materials & Mechanics Research Center (AMMRC)	0.020" thick 2024-T3 or T4 aluminum or 0.014" 5052 aluminum	10	5	5	125
	Alternate Requirement		same	14	7	7	150
MIL-STD-662D 19 March 1984	Ballistic Test for Armor	Army Materials & Mechanics Research Center(AMMRC)	0.020" thick 2024-T3 or T4 aluminum or 5052 aluminum	per TOP 2-2-710	per TOP 2-2-710	per TOP 2-2-710	per TOP 2-2-710
MIL-STD-662E 22 January 1987	Ballistic Test for Armor	Army Materials Technology Laboratory (formerly AMMRC)	0.020" thick 2024-T3 or T4 aluminum or 0.014" 5052 aluminum	4, 6, or 10†	2, 3, or 5	2, 3, or 5	60, 90, 100, 125

Notes:

* A copy of this standard was not available for review.

† The selection of the number of impacts and velocity spread is directed by the applicable procurement specification, the contracting officer, or the test engineer.

Appendix

Minitab Output Comparing the V_{50} Values Calculated Using the JTCG/AS Interlaboratory Test Data in Accordance with TOP 2-2-710

Table A1

Steel V_{50} Values with 1 Partial Penetration and 1 Complete Penetration in 50 fps

```
                                                 INDIVIDUAL 95 PCT CI'S FOR V50
                                                 BASED ON POOLED STDEV
  LAB    SHOTS      V50        STDEV   ----------+---------+---------+------
   1       2      1812.5       34.6                                 (-*-)
   2       2      1870.0       12.7                                   (--*-)
   3       2      1807.0        8.5                                (-*-)
   4       2      1656.5       27.6                        (-*-)
   5       2      1595.0       32.5                     (-*-)
   6       2      1258.0       25.5    (-*-)
   7       2      1837.5       33.2                                  (-*-)
   8       2      1583.5       20.5                    (-*-)
   9       2      1448.5       21.9            (-*-)
                                       ----------+---------+---------+------
POOLED STDEV =     25.6                        1400      1600      1800
```

TABLE OF PAIRWISE COMPARISONS

	1	2	3	4	5	6	7	8
2	-158.9 43.9							
3	-95.9 106.9	-38.4 164.4						
4	54.6 257.4	112.1 314.9	49.1 251.9					
5	116.1 318.9	173.6 376.4	110.6 313.4	-39.9 162.9				
6	453.1 655.9	510.6 713.4	447.6 650.4	297.1 499.9	235.6 438.4			
7	-126.4 76.4	-68.9 133.9	-131.9 70.9	-282.4 -79.6	-343.9 -141.1	-680.9 -478.1		
8	127.6 330.4	185.1 387.9	122.1 324.9	-28.4 174.4	-89.9 112.9	-426.9 -224.1	152.6 355.4	
9	262.6 465.4	320.1 522.9	257.1 459.9	106.6 309.4	45.1 247.9	-291.9 -89.1	287.6 490.4	33.6 236.4

Tukey's pairwise comparisons

```
    Family error rate = 0.0500
Individual error rate = 0.00336
```

Appendix

Minitab Output Comparing the V_{50} Values Calculated Using the JTCG/AS Interlaboratory Test Data in Accordance with TOP 2-2-710

Table A2

Steel V_{50} Values with 2 Partial Penetrations and 2 Complete Penetrations in 60 fps

```
                                        INDIVIDUAL 95 PCT CI'S FOR V50
                                        BASED ON POOLED STDEV
LAB   SHOTS     V50        STDEV    -------+---------+---------+---------
 1      4     1795.0       11.5                                (-*)
 2      4     1851.5       22.6                                    (*-)
 3      4     1823.0       22.3                                  (-*)
 4      4     1684.2       20.1                       (*-)
 5      4     1562.0       14.0              (*)
 6      4     1676.8       19.7                      (-*)
 7      4     1791.2       21.5                                (*-)
 8      4     1597.7       20.3                 (-*)
 9      4     1429.3       23.5     (*-)
                                    -------+---------+---------+---------
POOLED STDEV =      19.9                  1500      1650      1800
```

TABLE OF PAIRWISE COMPARISONS

	1	2	3	4	5	6	7	8
2	-103.8 -9.2							
3	-75.3 19.3	-18.8 75.8						
4	63.5 158.0	120.0 214.5	91.5 186.0					
5	185.7 280.3	242.2 336.8	213.7 308.3	75.0 169.5				
6	71.0 165.5	127.5 222.0	99.0 193.5	-39.8 54.8	-162.0 -67.5			
7	-43.5 51.0	13.0 107.5	-15.5 79.0	-154.3 -59.7	-276.5 -182.0	-161.8 -67.2		
8	150.0 244.5	206.5 301.0	178.0 272.5	39.2 133.8	-83.0 11.5	31.7 126.3	146.2 240.8	
9	318.5 413.0	375.0 469.5	346.5 441.0	207.7 302.3	85.5 180.0	200.2 294.8	314.7 409.3	121.2 215.8

Tukey's pairwise comparisons

```
    Family error rate = 0.0500
Individual error rate = 0.00231
```

Appendix

Minitab Output Comparing the V_{50} Values Calculated Using the JTCG/AS Interlaboratory Test Data in Accordance with TOP 2-2-710

Table A3

Steel V_{50} Values with 3 Partial Penetrations and 3 Complete Penetrations in 150 fps

```
                                               INDIVIDUAL 95 PCT CI'S FOR V50
                                                BASED ON POOLED STDEV
   LAB    SHOTS     V50         STDEV     ------+---------+---------+---------+
    1       6      1773.3       44.9                           (-*--)
    2       6      1850.0       33.5                                (-*--)
    3       6      1877.8       47.3                                  (-*--)
    4       6      1657.0       57.4                   (-*--)
    5       6      1556.3       48.2            (--*-)
    6       6      1643.7       55.2                  (--*-)
    7       6      1793.7       35.1                            (--*-)
    8       6      1601.7       22.5               (--*-)
    9       6      1450.2       41.2     (--*-)
                                          ------+---------+---------+---------+
POOLED STDEV =      44.1                       1500      1650      1800      1950
```

TABLE OF PAIRWISE COMPARISONS

	1	2	3	4	5	6	7	8
2	-159.6 6.3							
3	-187.4 -21.6	-110.8 55.1						
4	33.4 199.3	110.1 275.9	137.9 303.8					
5	134.1 299.9	210.7 376.6	238.6 404.4	17.7 183.6				
6	46.7 212.6	123.4 289.3	151.2 317.1	-69.6 96.3	-170.3 -4.4			
7	-103.3 62.6	-26.6 139.3	1.2 167.1	-219.6 -53.7	-320.3 -154.4	-232.9 -67.1		
8	88.7 254.6	165.4 331.3	193.2 359.1	-27.6 138.3	-128.3 37.6	-40.9 124.9	109.1 274.9	
9	240.2 406.1	316.9 482.8	344.7 510.6	123.9 289.8	23.2 189.1	110.6 276.4	260.6 426.4	68.6 234.4

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.00214

Appendix

Minitab Output Comparing the V_{50} Values Calculated Using the JTCG/AS Interlaboratory Test Data in Accordance with TOP 2-2-710

Table A4

Steel V_{50} Values with 5 Partial Penetrations and 5 Complete Penetrations

```
                                           INDIVIDUAL 95 PCT CI'S FOR V50
                                           BASED ON POOLED STDEV
 LAB    SHOTS      V50       STDEV  -----+---------+---------+---------+-
  1      10      1814.5      46.6                           (---*---)
  2      10      1834.0     118.2                            (---*---)
  4      10      1693.1      46.0                  (---*---)
  5      10      1503.3      53.7    (---*---)
  6      10      1513.8     192.8     (---*---)
  7      10      1745.8      96.0                     (---*----)
  8      10      1585.3      53.0         (----*---)
                                    -----+---------+---------+---------+-
POOLED STDEV =   100.2                  1500      1650      1800      1950
```

TABLE OF PAIRWISE COMPARISONS

	1	2	4	5	6	7
2	-156 117					
4	-15 258	4 278				
5	175 448	194 467	53 326			
6	164 437	184 457	43 316	-147 126		
7	-68 205	-48 225	-189 84	-379 -106	-369 -95	
8	93 366	112 385	-29 244	-219 55	-208 65	24 297

Tukey's pairwise comparisons

```
    Family error rate = 0.0500
Individual error rate = 0.00338
```

Appendix

Minitab Output Comparing the V_{50} Values Calculated Using the JTCG/AS Interlaboratory Test Data in Accordance with TOP 2-2-710

Table A5

Ceramic V_{50} Values with 1 Partial Penetration and 1 Complete Penetration in 50 fps

```
                                     INDIVIDUAL 95 PCT CI'S FOR V50
                                     BASED ON POOLED STDEV
    LAB    SHOTS    V50       STDEV  ---+---------+---------+---------+---
     1      2   1703.5       33.2            (--*--)
     2      2   1896.0        4.2                                 (--*--)
     3      2   1601.5        9.2   (--*--)
     4      2   1638.5       19.1      (--*--)
     5      2   1755.0       17.0                  (--*-)
     6      2   1876.0        7.1                               (--*--)
     7      2   1657.5       21.9        (--*--)
     8      2   1671.0       25.5         (--*--)
     9      2   1673.0        7.1         (--*--)
                                     ---+---------+---------+---------+---
POOLED STDEV =     18.5             1600      1700      1800      1900
```

TABLE OF PAIRWISE COMPARISONS

	1	2	3	4	5	6	7	8
2	-265.8 -119.2							
3	28.7 175.3	221.2 367.8						
4	-8.3 138.3	184.2 330.8	-110.3 36.3					
5	-124.8 21.8	67.7 214.3	-226.8 -80.2	-189.8 -43.2				
6	-245.8 -99.2	-53.3 93.3	-347.8 -201.2	-310.8 -164.2	-194.3 -47.7			
7	-27.3 119.3	165.2 311.8	-129.3 17.3	-92.3 54.3	24.2 170.8	145.2 291.8		
8	-40.8 105.8	151.7 298.3	-142.8 3.8	-105.8 40.8	10.7 157.3	131.7 278.3	-86.8 59.8	
9	-42.8 103.8	149.7 296.3	-144.8 1.8	-107.8 38.8	8.7 155.3	129.7 276.3	-88.8 57.8	-75.3 71.3

Tukey's pairwise comparisons

```
     Family error rate = 0.0500
Individual error rate = 0.00336
```

Appendix

Minitab Output Comparing the V_{50} Values Calculated Using the JTCG/AS Interlaboratory Test Data in Accordance with TOP 2-2-710

Table A6

Ceramic V_{50} Values with 2 Partial Penetrations and 2 Complete Penetrations in 60 fps

```
                                          INDIVIDUAL 95 PCT CI'S FOR V50
                                          BASED ON POOLED STDEV
  LAB    SHOTS     V50       STDEV    -------+---------+---------+---------
   1       4     1747.0      22.0                 (--*--)
   2       4     1781.0      11.5                      (--*--)
   3       4     1771.7      21.5                    (--*--)
   4       4     1683.7      24.7        (--*--)
   5       4     1754.5      24.1                  (--*--)
   6       4     1896.7      25.5                                    (--*--)
   7       4     1652.2      26.8     (--*--)
   8       4     1675.3      23.4       (--*--)
   9       4     1688.5      25.7         (--*--)
                                      -------+---------+---------+---------
POOLED STDEV =   23.2                      1680      1760      1840
```

TABLE OF PAIRWISE COMPARISONS

	1	2	3	4	5	6	7	8
2	-89.2 21.2							
3	-80.0 30.5	-46.0 64.5						
4	8.0 118.5	42.0 152.5	32.8 143.2					
5	-62.7 47.7	-28.7 81.7	-38.0 72.5	-126.0 -15.5				
6	-205.0 -94.5	-171.0 -60.5	-180.2 -69.8	-268.2 -157.8	-197.5 -87.0			
7	39.5 150.0	73.5 184.0	64.3 174.7	-23.7 86.7	47.0 157.5	189.3 299.7		
8	16.5 127.0	50.5 161.0	41.3 151.7	-46.7 63.7	24.0 134.5	166.3 276.7	-78.2 32.2	
9	3.3 113.7	37.3 147.7	28.0 138.5	-60.0 50.5	10.8 121.2	153.0 263.5	-91.5 19.0	-68.5 42.0

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.00231

Appendix

Minitab Output Comparing the V_{50} Values Calculated Using the JTCG/AS Interlaboratory Test Data in Accordance with TOP 2-2-710

Table A7

Ceramic V_{50} Values with 3 Partial Penetrations and 3 Complete Penetrations in 150 fps

```
                                         INDIVIDUAL 95 PCT CI'S FOR V50
                                         BASED ON POOLED STDEV
   LAB    SHOTS     V50        STDEV    -+---------+---------+---------+-----
    1       6      1741.3      21.1                (---*---)
    2       6      1845.0      54.6                           (---*--)
    3       6      1804.3      48.5                       (--*---)
    4       6      1694.5      28.6            (--*---)
    5       6      1760.8      43.7                  (---*---)
    6       6      1906.0      49.7                                 (---*--)
    7       6      1634.0      53.8     (--*---)
    8       6      1669.2      39.8        (---*---)
    9       6      1692.3      46.1           (--*---)
                                        -+---------+---------+---------+-----
POOLED STDEV =      44.2             1600      1700      1800      1900
```

TABLE OF PAIRWISE COMPARISONS

	1	2	3	4	5	6	7	8
2	-186.9 -20.5							
3	-146.2 20.2	-42.5 123.9						
4	-36.4 130.0	67.3 233.7	26.6 193.0					
5	-102.7 63.7	1.0 167.4	-39.7 126.7	-149.5 16.9				
6	-247.9 -81.5	-144.2 22.2	-184.9 -18.5	-294.7 -128.3	-228.4 -62.0			
7	24.1 190.5	127.8 294.2	87.1 253.5	-22.7 143.7	43.6 210.0	188.8 355.2		
8	-11.0 155.4	92.6 259.0	52.0 218.4	-57.9 108.5	8.5 174.9	153.6 320.0	-118.4 48.0	
9	-34.2 132.2	69.5 235.9	28.8 195.2	-81.0 85.4	-14.7 151.7	130.5 296.9	-141.5 24.9	-106.4 60.0

Tukey's pairwise comparisons

```
    Family error rate = 0.0500
Individual error rate = 0.00214
```

Appendix

Minitab Output Comparing the V_{50} Values Calculated Using the JTCG/AS Interlaboratory Test Data in Accordance with TOP 2-2-710

Table A8

Ceramic V_{50} Values with 5 Partial Penetrations and 5 Complete Penetrations

```
                                       INDIVIDUAL 95 PCT CI'S FOR V50
                                       BASED ON POOLED STDEV
   LAB    SHOTS     V50      STDEV   --------+---------+---------+--------
    1      10     1760.1      39.2           (------*-------)
    2      10     1974.6     310.4                         (-------*------)
    4      10     1705.7      47.2      (-------*------)
    5      10     1757.9      39.6           (------*-------)
    6      10     1872.2     121.1                    (-------*------)
    7      10     1656.6      33.4   (------*-------)
    8      10     1710.9      43.6      (-------*-------)
    9      10     1908.1     378.4                        (------*-------)
                                     --------+---------+---------+--------
POOLED STDEV =    181.2                    1650      1800      1950
```

TABLE OF PAIRWISE COMPARISONS

	1	2	4	5	6	7	8
2	-468 39						
4	-199 308	16 522					
5	-251 255	-37 470	-305 201				
6	-365 141	-151 356	-420 87	-368 139			
7	-150 357	65 571	-204 302	-152 355	-38 469		
8	-204 302	10 517	-258 248	-206 300	-92 415	-308 199	
9	-401 105	-187 320	-456 51	-403 103	-289 217	-505 2	-450 56

Tukey's pairwise comparisons

Family error rate = 0.0500
Individual error rate = 0.00258

Acknowledgments

The Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) provided funding for this program. The JTCG/AS is a chartered activity under the aegis of the Joint AMC/NC/AFLC Logistics Commanders. The JTCG/AS Project ID number is V-3-A1, *Aircraft Armor Materials Testing and Data Reporting Standards Project*. We especially acknowledge Mr. Joseph P. Jolley, the Army Representative to the JTCG/AS Central Office and LTC John N. Lawless Jr., the Director of the JTCG/AS Central Office.

The authors gratefully acknowledge the participation by the following people and organizations who performed the ballistic tests:

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Mr. Stephen Hanchack, Mr. Ronald Hoffman, and Mr. Gary Abfalter
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We also benefited from and recognize the thoughtful and productive discussions with the following individuals: Mr. Eldridge E. Rowe of the Naval Surface Warfare Center, Dahlgren, VA; Mr. Earl Wilhelm of the Boeing Defense & Space Group; Dr. Barry E. Bodt of the U.S. Army Research Laboratory Advanced Computational & Information Sciences Directorate; Mr. William A. Gooch Jr. and Mr. Edward J. Rapacki of the U.S. Army Research Laboratory, Weapons Technology Directorate; Dr. Eric B. Kula, Dr. Martin G.H. Wells, Dr. Ralph P.I. Adler, Dr. Jonathan S. Montgomery, Dr. Joseph Prifti, Dr. Albert Chang, Mr. Albert A. Anctil, Mr. William E. Haskell III, and Mr. James Mackiewicz of the U.S. Army Research Laboratory Materials Directorate; Mr. Ellory Sanderson and Mr. Todd M. Wagner of the U.S. Army Combat Systems Test Activity; Dr. Mark Vangel of the National Institute for Standards and Technology; Dr. Marc A. Adams and Dr. James G. Zwissler of the Jet Propulsion Laboratory, California Institute of Technology.

References

1 American Society for Testing and Materials Standard E691-92, *Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method*. January 1992.

2 Golub, A. and Grubbs, F., *On Estimating Ballistic Limit and its Precision*, Ballistic Research Laboratory Technical Note No. 151. March 1950.

3 Feroli, J.A., *The Accuracy and Reproducibility of Several Methods for Obtaining Ballistic Limits of Armor (U)*, Aberdeen Proving Ground, Development and Proof Services, Report No. DPS/TB4-005D, May 1957.

4 Langlie, H.J., *A Reliability Test Method for One-Shot Items*, Publication No. U-1792, Aeronutronic Reliability Department, 10 August 1962.

5 McLaughlin, G.J. and Labbé, J.C., *An Improved Method of Estimating The Critical Velocity of a Projectile in Penetration Ballistics*, Defence Research Establishment, Valcartier, DREV R-668/72, August 1972.

6 Graves, John H.; Anctil, Albert A.; Pothier, Brian. *Design Fabrication and Testing of Modular Armor for Defeat of 12.7 mm API and 23 mm HEI Threats.*(U) Proceedings of the American Defence Preparedness Association Second Ballistics Symposium on Classified Topics. October 26-29, 1992. pp. 289-297. SECRET.

7 Mascianica, Francis. *Ballistic Technology of Lightweight Armor* .(U) U.S. Army Research Laboratory, AMMRC TR 81-20, March 1981. CONFIDENTIAL.

8 MIL-STD-662E, V_{50} Ballistic Test for Armor. U.S. Army Research Laboratory, Materials Directorate, Watertown, MA, 22 January 1987, pg. 5.

9 Test Operations Procedure 2-2-710, Ballistic Tests of Armor Materials, U.S. Army Test and Evaluation Command, Aberdeen, MD, 7 February 1984.

10 *CRC Standard Mathematical Tables,* 25th Edition, ed: William H. Beyer, CRC Press, Inc., Boca Raton, FL, pg. 513.

11 *CRC Standard Mathematical Tables*, pg. 520.

12 DPS-2862, Final Report on Determination of Zone of Mixed Results for Various Armor Materials, September 1968.

13 *CRC Standard Mathematical Tables*, pg. 521.

14 American Society for Testing and Materials Standard E177-90a, *Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods* June 1990.

15 Hickey, Charles F. Jr. and Anctil, Albert A. *Split Heat Mechanical Property Comparison of ESR and VAR 4340 Steel*. AMMRC TR 83-27, May 1983.

16 Hickey, Charles F. Jr. and Thomas, Timothy S. "Comparing a Split Heat of ESR/VAR 4340 Steel." *Metal Progress*. October 1985.

17 Mascianica, Francis, pg. 156.

18 Anctil, Albert A. and Graves, John, H. Ballistic Tests of Armor Systems for the Aircraft Modular Armor Program. U.S. Army Materials Technology Laboratory, Watertown, MA MTL TR 90-33. pg. 4. June 1990. CONFIDENTIAL.

19 Mannschreck, W.A. *Aircraft Armor for Defeat of Combined Threat: Interim Report.*(U) Naval Surface Warfare Center, Dahlgren, VA. NSWC TR 80-258. pg. 27. July 1980. CONFIDENTIAL.

20 Rupert, Nevin L. *Aircraft Armor for Defeat of Combined Threat: Second Interim Report.*(U) Naval Surface Warfare Center, Dahlgren, VA. NSWC TR 81-226. pg. A-4. July 1981. CONFIDENTIAL.

21 Lapin, Lawrence L. *Probability and Statistics for Modern Engineering,* PWS-KENT Publishing Company, Boston MA, 1990, pg. 570.

22 Minitab Inc., *MINITAB Statistical Software,* Release 8.21, PC Version, 1991.

23 Miller, Rupert, *Beyond ANOVA: The Basics of Applied Statistics*, Wiley, New York, 1986.

24 Devore, Jay L., *Probability and Statistics for Engineering and the Sciences,* Brooks/Cole Publishing Company, Pacific Grove, CA, 1991, pps. 371-392.

25 Beatty, J.H. Unpublished data.

26 Engineering Design Handbook: Armor & Its Applications(U). U.S. Army Materiel Command. AMCP 706-170. November 1973. SECRET.

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